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THE RESURRECTION OF NEUTRINOS AS DARK MATTER

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"Rumors of my death are greatly exaggerated" – Mark Twain

Abstract

It is shown that new observations of large scale structure in the Universe (voids, foam, and large-scale velocity fields) are best understood if the dominant matter of the Universe is in the form of massive ($9eV \lesssim m_\nu \lesssim 35eV$) neutrinos. Cold dark matter, even with biasing, seems unable to duplicate the combination of these observations (although a fine-tuned loophole with cold matter and percolated explosions may also marginally work.) The previous fatal problems of galaxy formation with neutrinos can be remedied by combining them with either cosmic strings or explosive galaxy formation. The former naturally gives the scale-free correlation function for galaxies, clusters, and superclusters, and gives large, but not necessarily spherical voids. The latter naturally gives spherical voids, but requires fine tuning and percolation to get the large scales and the scale-free correlation function.

Massive neutrinos were once quite popular as candidates for solving the cosmological dark matter problem, since they were the least exotic of the non-baryonic options, and they naturally clustered only on large scales where the dark matter was needed, rather than on the small scales where the contribution of dark matter was known to be minimal (ref. 1 and references therein). They received a major boost with the preliminary reports of measured mass (ref. 2 and references therein) for ν_e (although probably only the most massive ν is cosmologically important, and that might well be ν_τ which could still have a $\sim 10eV$ mass, even if $m_{\nu_e} \ll 1eV$). Also, they gained strength when it was shown[3] that the neutrino Jean's mass was

$$M_J \sim \frac{3 \times 10^{18} M_\odot}{m_\nu^2(eV)} \text{ or } \lambda_J \sim \frac{1300 Mpc}{m_\nu(eV)}$$

which for $m_\nu \sim 30eV$ yielded $M \sim 3 \times 10^{15} M_\odot$, and $\lambda \sim 40 Mpc$, the mass and scale of superclusters.

Unfortunately, massive neutrinos fell into disrepute as dark matter when it was emphasized[4] that in the standard adiabatic model of galaxy formation with a random phase, Zel'dovich fluctuation spectrum of the type expected by inflation, and with $\delta T/T$ constrained by microwave observations, galaxies did not form until redshift $z \lesssim 1$. This occurred because the initially formed pancakes with mass M_J took a while to fragment down to galaxy size. This contradicted the observations which showed that quasars existed back to $z \sim 3.5$. In addition, if baryons stay in gas form in the potential wells of the large ν pancakes, they light up in the x-rays beyond what is observed[5].

While some[6] have appealed to statistical tails, etc., to escape these conclusions, most cosmologists began abandoning neutrinos and adopting cold dark matter[7], which could enable rapid galaxy formation[8,9].

Cold matter also had its problems[10]. In the standard model, it would all cluster on small scales, and thus be measured by the dynamics of clusters, such as the Virgo infall. Since such measurements implied that $\Omega \sim 0.2 \pm 0.1$ on cluster scales, this meant that $\Omega_{cold} \lesssim 0.3$, and not unity. Remember that $\Omega_{baryon} \sim 0.1$, so observationally, non-baryonic dark matter is not required unless one wants an Ω of unity, so cold matter wasn't naturally solving one problem for which it was postulated. This constraint on cold matter could be escaped if it were *also* assumed that galaxy formation was biased[9,11] and did not occur everywhere. Thus, there could be many clumps of cold matter and baryons that did not shine for some ad hoc reason. Biasing ran into problems when it could not explain the observation[12] of a very large cluster–cluster correlation function, ξ_{cc}, relative to the galaxy–galaxy

correlation function[10,11], ξ_{gg}. With biasing $\xi_{cc} \propto \xi_{gg}$ but in all models $\xi_{gg} < 0$ for a few 10's of Mpc, whereas ξ_{cc} was observed to be positive out to scales $\gtrsim 50Mpc$.

Hardcore cold matter lovers had to argue that the ξ_{cc} data might be wrong, although no one has been able to disprove it. A way out of the ξ_{cc} problem was proposed in Reference 13. There we noted that the correlation functions appear to be scale free, thus implying that large-scale structure is dominated by something other than random noise and gravity, say either percolated explosions or strings. In fact, the scale-free structure is characterized by a fractal of dimension $D \sim 1.2$, not too different from the $D \sim 1$ that naive string theory might yield. String calculations[14] of galaxy formation indeed found support for such a fractal process with the appropriate dimension being valid from galaxy to supercluster scales.

Thus, there were already strong hints that something was wrong with the previous, in vogue, picture of biasing and cold matter with random noise initial fluctuations. To this we now add the new observations of many large voids[15,16] of diameter $50h_{1/2}Mpc$ ($h_{1/2} \equiv H_0/50km/sec/Mpc$), with most galaxies distributed on the walls of the voids, and the observation[17] that our local 40 Mpc region of space is moving with a coherent velocity field of $\sim 600km/sec$ toward Hydra-Centaurus. While at least one large void (in Böotes) had been observed before[18], using a pencil beam approach, until the Harvard redshift[15] survey work, it was not known how ubiquitous voids were. In fact, the Harvard data shows that almost all galaxies are distributed along the "walls" of voids; galaxies and clusters are not randomly distributed, but fit onto a well-ordered pattern.

While the Harvard work only goes out to $\sim 100Mpc$, there is substantial evidence that this sort of pattern persists to redshifts $z \sim 1$ from the Koo and Kron survey[16], as well as the earlier work of Tifft and others on distributions of quasar redshifts which showed "quantization". A simple explanation for the peaks and valleys in the distribution of galaxies and quasars with redshift is that one is looking through filaments or shells with voids in between, once again demonstrating that galaxies and clusters are not laid out randomly on the sky, but follow a pattern.

While statistical fluctuations with cold matter might yield a few large voids as well as many small voids[5,9], it is difficult to get all of space filled with large voids and have galaxies appear only at the boundaries unless some special form of "biasing" is used. However, the real killing blow for the cold matter plus biasing scheme comes from the velocity field work. Even if the biasing could be selected so as to give ubiquitous large voids, the velocities of a $40Mpc$ region of galaxies would be relatively small and random, rather than large and coherent[19]. Thus, it appears

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that the large-scale structure is telling us that we need something that gives us $\sim 40 Mpc$ coherent patterns, and cold matter doesn't appear the way to go.

Since neutrinos naturally gave us patterns on this scale, maybe they should be reexamined. In addition, since the voids look rather spherical, and since explosions tend to produce spherical holes after a few expansion times even if the initial explosion is asymmetric, perhaps an explosive mechanism should be considered also. Since the Ostriker–Cowie[20] explosion mechanism by itself cannot yield such large voids, the only way it could work is via a high density network of explosions which ¡percolated[10,21]. However, to get $\Omega = 1$ with an exploding scenario would still require non-baryonic matter that did not cluster with the light emitting stuff. In principal, this could be either neutrinos or cold matter but at least with neutrinos an $\sim 40 Mpc$ scale might still be naturally imposed.

Of course, in order for neutrinos to work as the dominant matter, some mechanism to rapidly form galaxies must be imposed both to enable galaxies to exist at $z \sim 5$, and to condense out the gas before it falls into the forming deep potential wells, and emits x-rays. Two ways that might achieve this rapid formation are either via the aforementioned explosion scheme within the collapsing ν-pancakes, or via cosmic strings[22] which would act as nucleation sites for galaxy formation. Since strings are not free-streamed away by the relativistic neutrinos[23], the galaxy scale fluctuations remain within the ν-pancakes. Notice that since neutrinos are not used by themselves simple arguments based on relating their primordial fluctuation spectrum to observed galaxy velocity and distribution features are not necessarily valid and must be reexamined in the more complete scenario.

To summarize, the above possibilities leaves us with two viable options: 1. Neutrinos and strings; or 2. Neutrinos and percolated explosions. A third option of cold matter and percolated explosions cannot be completely dismissed, but does not naturally give us the $\sim 40 Mpc$ scale; however, the explosions could be a way of clearing the baryons out of the cold matter clumps in the voids and leave a critical density of matter not associated with the light emitting regions. In such a scenario, the voids would then be filled with clumps of cold matter.

It is interesting that the two most viable options involve the same two options that the scale-free cluster–cluster correlation function arguments point towards. Let us look at each of these scenarios in a little more detail and see if there might be ways of resolving whether either of them might actually be correct. Also, let us see what each requires for the physics of the early Universe.

Both of these scenarios have hot matter, presumably neutrinos as the dominant matter of the Universe. If $\Omega = 1$, as is necessary to avoid our living at a special epoch, and as agrees with the recent large-scale galaxy count arguments of Loh and Spillar (but disagrees with the direct dynamical arguments on scales of clusters and smaller, and with the baryonic measurements from nucleosynthesis), then $m_\nu \lesssim 35eV$. Since with $\Omega = 1$ the age of the Universe $t_0 = \frac{2}{3H_0}$, and since globular clusters and nucleochronology require $t_0 \gtrsim 11 \times 10^9 yr$ (with a best fit of $t_0 \sim 15 \times 10^9 yr$) we must say that $H_0^{-1} \gtrsim 17 \times 10^9 yr$. Thus, $H_0 \lesssim 60km/sec/Mpc$, or $h_{1/2} \lesssim 1.2$. From the number of neutrinos and photons in the Universe, we know that the most massive neutrino is bounded by (see ref. 1 and references therein)

$$m_\nu \lesssim (25eV)\Omega h_{1/2}^2 \lesssim 35eV.$$

It is curious that the requirement that we want the neutrinos to give us the large-scale structure, $\lambda_J \sim 40Mpc$, or $M_J \sim 10^{16}M_\odot$, also gives us $m_\nu \sim 30eV$, a mass about what is necessary to get $\Omega \sim 1$. Also, we have a lower bound from the nucleosynthesis argument[26] that the number of neutrino species with $m_\nu \lesssim 10MeV$ is three or at most four. Since the sum of all neutrino masses cannot exceed the $35eV$ limit mentioned above, and since the lowest mass for the most massive one occurs when they are all equal, then if $N_\nu \leq 4$,

$$m_\nu \gtrsim 9eV.$$

The first scale to be able to condense and thus have their density grow will be the horizon scale when the neutrinos become non-relativistic, which is M_J. However, in the string option, loops of string will exist down to scales of galaxy size (scales smaller than galaxy size gravitationally radiate away[22]). So as the neutrinos become non-relativistic they can be trapped on smaller scales. The baryons will not be able to begin clustering until after recombination. However, the slow-moving baryons will rapidly fall on to the pre-existing loops of string plus neutrinos. Thus, galaxies will be able to form shortly after recombination, and well before $z \sim 1$.

The correlation functions of galaxies through superclusters will be characterized by the string picture[14] and will naturally yield a fractal near $D \sim 1$. The collapsing ν-pancakes on $\lambda_J \sim 40Mpc$ scales will create large voids on that scale, and leave galaxies in planes. Although actual detailed evolutionary calculations of ν-pancakes plus string-induced galaxy formation remain to be completed. Whether or not these planes and voids evolve to spherical holes remains to be proven (or whether the observed holes are spherical). Of course, in many models voids do tend towards a

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spherical shape after several expansion times. Thus, one might use the degree of sphericity versus z to say something about the nature of the origin of the voids.

While this string plus neutrino scenario naturally yields $D \sim 1$, it does not so naturally give $D = 1.2$. Fine tuning[28] of string parameters may enable such variation on the scale of the galaxy–galaxy correlation function, or some modification of the criteria for the formation of light-emitting regions around the strings may be necessary.

In this regard it should be remembered that because of possible systematic errors, not everyone agrees that 1.2 is significantly different from 1.0, even for the galaxy–galaxy correlation function, which is the best determined[30]. The uncertainties in the exponent of the cluster–cluster correlation functions are *far* larger, thus problems in trying to explain variations from $D = 1$ fractals are not serious at the present time. With strings there is the additional problem of tuning the primordial phase transition so as to inflate first, and then produce strings[38]. While not impossible, this is constraining.

The second way to get neutrinos to work involves explosive galaxy formation. Here we need initial seeds to lead to condensations which produce massive baryonic objects which explode. Under the third option, where the explosions are used with cold matter, the baryons might naturally collect around the growing small-scale (globular cluster mass) cold matter clumps. However, as mentioned before, such a model does not naturally give us $40 Mpc$ structure. If we use neutrinos then the seeds must be in a form which does not get free-streamed away by the relativistic neutrinos. Strings don't work well here because the string scales that might lead to rapidly evolving baryonic objects are radiated away gravitationally. Thus, the seeds must come in some other isothermal-like form. Perhaps the best option would be condensates from the quark–hadron transition, either planetary mass black holes[31] or Witten nuggets[32]. Both have formation problems[33] and the latter have survival problems[34] also. If such objects could form and survive, they do lead naturally[35] to very massive ($\sim 1000 M_\odot$) baryonic objects which would explode on rapid timescales.

The scale affected by explosions of single galaxy size[36] is at most a few Mpc; however, it has been shown[21] that at sufficiently high densities and high trigger rates, the explosions can percolate at least out to scales of a few 10's of Mpc. The fractal dimension of such percolated ensembles is quite sensitive to parameter assumptions and usually varies with scale, thus showing that it is not a true scale-free fractal. If it is made to fit the small scale (few Mpc) with $D \sim 1$ it is usually

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larger ($D \sim 2$) on scales of $\gtrsim 10Mpc$. Since, as mentioned above, the exponent of the cluster–cluster correlation function is not, at present, well determined, such models cannot be ruled out. With such explosions percolating within ν-pancakes, we might naturally have their pattern superimposed on the $\sim 40Mpc$ neutrino scale. In addition, although percolated explosions will initially be highly non-spherical, their shape will evolve towards sphericity with the smaller axes catching up in length to the largest one. In order for large-scale percolation to occur, several generations[21] of explosions must occur; however, cooling arguments and time to initial explosions, plus the need for condensed objects by $z \sim 4$ and the need to hide from present observers, the radiation produced by the explosions, severely restrict the possibility of such percolation and thus quite a bit of fine tuning is required to escape the constraints.

Thus, while we cannot explicitly rule out this latter case, unless some new physics can be developed to show how the fine-tuned parameters are natural for other reasons, we must lean towards the string option as the present frontrunner. Strings, of course, would have other observational consequences (see ref. 22 and references therein) like gravitational double lensing of distant objects and shifts in the 3° background across such a line of lenses, and a background of gravitational radiation from the evaporation of small-scale strings which might affect the millisecond pulsar. Thus, observations should eventually be able to confirm or deny this frontrunner.

In summary, we have come full circle and once again massive neutrinos are looking good. However, with them comes the need for galaxy and structure formation triggered by something other than random phase adiabatic fluctuations. The non-random phase fractal initial conditions such as produced by strings[37] or fractal generating explosions[20,21] seem to be the way to go. It is comforting that the exotica of cosmic strings do seem to be a natural consequence[39] of the current, in vogue, superstring Theories of Everything (T.O.E.).

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